UTILIZING DOPPLER ULTRASOUND TO DETECT ARTERIOLE BLOOD FLOW WITHIN THE MEDIAN NERVE SHEATH

THESIS

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By

Kathryn Zale, B.A., RDMS

The Ohio State University

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Graduation with Distinction Examination Committee:

Dr. Kevin D. Evans, Advisor

Dr. Steffen Sammet

ABSTRACT

Diagnostic medical sonographers (DMS) are at an increased risk for developing work-related musculoskeletal disorders, such as carpal tunnel syndrome (CTS). CTS is characterized by inflammation of the median nerve within the carpal tunnel and a literature review supports that hypervascularization is seen within the nerve sheath. Currently, only invasive procedures such as nerve conduction testing and dynamic contrast magnetic resonance imaging are utilized in diagnosing CTS. This feasibility study was the first of its kind to detect and quantify arteriole blood flow within the median nerve with spectral and power Doppler ultrasound. Five DMS had their wrists scanned with a hand carried ultrasound unit over a 10-week period both before and after scanning neonatal heads. The results showed the qualitative measure of blood flow with color Doppler was consistently seen on each scanning session, whereas the quantitative measure with spectral Doppler was obtained only half of the time. The pre and post measures of peak systolic (PS) velocity and end diastolic (ED) velocity were not statistically significant, but showed very low blood flow on average - PS = 4.36 cm/s and ED = 0.76 cm/s. While these measures were not consistently obtained, this study proved acquiring quantitative blood flow within the median nerve with spectral Doppler ultrasound is feasible. There were many limitations of this study and key among these was the short evaluation, nested inside a larger work day. This was a feasibility study; therefore a more rigorous controlled study is needed to find the true sensitivity of spectral Doppler ultrasound to quantify blood flow in the median nerve. A longitudinal and comprehensive data collection is needed that reflects the entire work load. Therefore, this research underlines the importance of understanding the related physiology and technique to find a noninvasive alternative in diagnosing CTS.

ACKNOWEDGEMENT

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Last, but not least I must thank my husband, Peter, and my parents, who encouraged me to study ultrasound and have helped support me through many years of education.

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CHAPTER 1

INTRODUCTION

Introduction

According to the National Institute of Occupational Safety and Health (NIOSH) diagnostic medical sonographers (DMS) are at an increased risk for developing work-related musculoskeletal disorders (WRMSD). [1] Among the highest reported musculoskeletal disorders by DMS is carpal tunnel syndrome or CTS[2] which is a common peripheral entrapment neuropathy characterized by nerve compression caused by elevated pressure in the carpal tunnel.[3]

This study was part of a larger collaborative pilot study (now in print) to determine and prevent the causative factors which contribute to the risk of developing CTS by comparing the DMS self-reported symptoms to psychosocial stressors, work demands, cognitive, behavioral, and physiological factors.[4] The study evaluated DMS who image the neonatal brain in an intensive care unit. DMS are required to place their arms inside the neonate's isolette to image the brain, ruling out any intracranial hemorrhage and tissue necrosis.[5] This work requires precise and tedious hand and body positioning which could contribute to WRMSD (Figure 1.1 and Figure 1.2).

While this overall pilot study was the first of its kind to make a quantitative analysis of the work stressors which could culminate in CTS in DMS, this independent study was also the first of its kind to detect and quantify arteriole blood flow, representative of inflammation, within the median nerve sheath of DMS utilizing both power Doppler and spectral Doppler.

Problem Statement

WRMSD are prevalent within the DMS population and it is reported over 90% of DMS scan in pain and up to 20% will eventually experience a career ending injury.[6] This poses a serious threat to the employed DMS. A combination of the following factors are present in the everyday practice of DMS - high repetition, high levels of force, direct pressure, awkward joint position, vibration, prolonged twisted position and others.[7] All of these factors could contribute to an increased risk of WRMSD.

In a studied sample of cardiac sonographers, a significant direct correlation was noted between symptoms of CTS and high hand grip pressure.[8] CTS is the most common entrapment neuropathy[9] and it is also recognized as one of the most important causes of workplace morbidity.[3]

The current gold standard in diagnosing CTS and nerve damage is nerve conduction velocity (NCV), which is an invasive procedure, requiring needles to be inserted under the skin[3]. Likewise, dynamic contrast enhanced MRI is invasive and has other drawbacks including cost, allergic reactions to contrast, claustrophobia, long scan times, and can be contraindicated in patients with cardiac pacemakers or certain metallic implants and those patients disabled and unable to be placed in an MRI unit.[10] The ability to detect and quantify hypervascularization with ultrasound sonography would provide for a cheaper, portable, non-invasive, non-radiating modality to be utilized for future detection of hypervascular arteriole flow, which could be applicable in detecting and perhaps predicting CTS.

Background

Recent studies have begun to utilize diagnostic sonography by comparing it to NCV for the detection of CTS. All of the studies concluded that by pairing ultrasound with NCV both their diagnostic sensitivity and specificity improved.[11-14] The best reported criterion for diagnosis has been

by obtaining the cross-sectional area of the median nerve. The diagnostic parameter for CTS is a nerve area measurement $\geq 10mm^2$, calculated at the proximal carpal tunnel (Figure 1.3). [15,16]

In addition, nerve entrapment can be caused by tendonitis and swelling within the tunnel causing a bulging of the transverse carpal ligament and compression on the median nerve. A sonogram of the cross-section at the hamate level can indicate bulging by drawing a line from the hook of the hamate to the tubercle of the trapezium and taking the measurement at 90 degrees from this line to the most anterior portion of the ligament. Measurements > 4 mm indicate CTS (Figure 1.4).[17]

While gray-scale sonography can evaluate the above measurements of the compressed and already swollen median nerve, it is important to understand the vascular component that contributes to CTS. The median nerve is well vascularized with endoneural and epineural microvascularization like other peripheral nerves. CTS is believed to be initiated with venous congestion of the median nerve followed by nerve edema and then impairment of the blood supplies. Studies have looked at this blood flow in the median nerve and have highlighted the vascular cause of carpal tunnel syndrome. Therefore, by detecting the vascular component of CTS there is an uncovering of a functional disturbance rather than the morphological altering of the median nerve.[3]

Diagnostic medical sonography includes the use of Doppler which is used to detect blood flow. The Doppler effect can be measured using the generated frequency of the beam relative to the travel of red blood cells as they move past the point of reference. Currently, there are three types of Doppler that can be processed by the ultrasound machine. The first is color Doppler, which detects blood flow and uses two colors, like red and blue, to distinguish between bidirectional flow of blood in relation to the transducer. The second form is pulsed-wave or duplex Doppler which gives a spectral wave form and quantitative wave of the blood flow, including the peak systolic and end

diastolic measures. Finally, power Doppler is a newer method which is similar to color Doppler, but the display is unidirectional, often this is represented in red. Power Doppler is currently the most sensitive to low flow states and tissue movement, which may cause flash artifacts.[18]

Review of Literature

There were a small number of published studies available which use color and power Doppler to detect arteriole flow, or inflammation. As stated before, this was a relatively unchartered area of research, so unfortunately, not all of them are pertinent to the median nerve. For this reason the reviewed literature will be explained in terms of its relevance to the work of detecting arteriole flow in the median nerve sheath

The most relevant study was published by Mallouhi et al in Austria, in which color Doppler and gray-scale sonography were used to predict CTS. A total of 206 wrists in 151 patients were examined with sonography and the diagnosis of CTS was confirmed in 172 wrists by the gold standard of NCT. Using logistic regression, the color Doppler detection of intraneural hypervascularization was the only variable that independently predicted median nerve involvement. It had the highest accuracy (95%) among all of the sonography criteria, including the median nerve cross-sectional area (91% accuracy). Color Doppler detected 174 wrists with intraneural blood vessels and correctly identified CTS in 164. The authors concluded that nerve hypervascularization and nerve swelling yielded the best detection of CTS. They went on to say this hypervascularization in the median nerve permitted recognition of CTS even before nerve edema, which may improve prognosis with early detection. Ultimately they supported Doppler sonography as a noninvasive mean to evaluate patients with suspected CTS.[3]

While this study was encouraging and closely related to the completed work, the assessment of color Doppler was not qualitative. Instead the evidence of hypervascularization in the median

nerve was based on Doppler presence (and then graded subjectively) or absence. Another downside to this study in relation to the given work is neither power nor spectral Doppler was utilized. In this case, if no spectral wave is seen the work cannot be quantified as showing arteriole blood flow. While this study is not quantitative it does look directly at CTS and median nerve vascularization. Most importantly it compares the accuracy of color Doppler to the gold standard NCV.

The next level of evidence was the use of magnetic resonance imaging (MRI) and its' applicability to the median nerve and CTS. Sugimoto et al used dynamic contrast enhanced MRI studies to evaluate CTS and concluded abnormal enhancement of the median nerve which pointed to hypervascularization as a reliable indicator of CTS. This study compared their results with MRI to the gold standard, NCT, and provide more evidence that median nerve hypervascularization is an indicator of CTS. While this study did not use Doppler sonography, it exemplifies how arteriole flow can be detected and compared as an indicator of compartment swelling that contributes to CTS.[19]

Further support in using sonography to detect low blood flow is a study by Terselev et al which compared 196 wrists and finger joints in patients affected by rheumatoid arthritis (RA) by means of color Doppler and postcontrast MRI to detect inflammation. The vascularization seen with the color Doppler was quantified by using a color recognition function, expressing a percent of color pixels in relation to the region of interest (ROI). It concluded there was a high significant association between the ultrasound Doppler indices of inflammation and postcontrast MRI scores.[20]

While this study was done in a wrist and finger joint space, CTS was not the main driver of the inflammation. While RA is a disease process and CTS a result of repetitive stress, both involve inflammation within a joint space. Unlike the previous Doppler sonography study there was an attempt to quantify the hypervascularization by using the ROI color percent. Again, while stated as

quantitative, no blood flow is strictly proven, as the sensitivity of the Doppler could be increased to the point that artifact from movement is confused with actual blood flow.

Finally, a retrospective study was conducted looking at the use of intraoperative sonography on dogs undergoing spinal cord surgery. Power Doppler was used and detected microcirculation within the spinal cord and the surrounding tissue, stating the communication was well defined and visible pulsatility during systole was seen. Ultrasound was discussed as a good modality for looking at microcirculation in detecting vascular flow within the nerve root and spinal cord intraoperatively.[21]

This study showed the ability of sonography to detect blood flow within a nerve sheath, albeit not the median nerve, but a nerve nonetheless and this power Doppler was described as pulsatile, which is what the proposed work quantifies in the human subject.

This brief literature review represents the need to quantify arteriole blood flow in the median nerve. The gap in the literature points out the lack of spectral Doppler used to document arteriole flow. No gain settings or pulse repletion frequency are given in all but one of the above mentioned studies. Previous research studies lack the rigor and reproducibility that is needed to translate to clinical practice and to develop a quantitative diagnostic parameter.

Research Objectives

The main objective of this research study was to determine if arteriole blood flow could be detected and quantified by the use of power and spectral Doppler sonography, within the median neural sheath. If this information was quantifiable, secondary objectives were to determine a correlation of Doppler flow with the DMS reported levels of pain and calculate the pulsatility and resistive indices of the spectral Doppler waveform.

Preliminary Data

Preliminary data was collected by Dr. Kevin Evans and his doctoral student, Shawn Roll, both have been trained in musculoskeletal sonography. Dr. Evans is the PI for this study and together Evans and Roll collected data for this pilot study. The results of the pre-pilot study showed a strong inter-rater reliability between both their sonograms and measurements of the median nerve.[4] Figures 1.5 and 1.6 are sonograms taken by the PI with the proposed ultrasound machine to demonstrate resolution and the machine's ability to gather blood flow data taken within the median nerve with power and spectral Doppler.

Figure 1.1: DMS conducting a neonatal sonography exam inside a neonatal isolette.
(Image courtesy of Dr. Evans)

Figure 1.2: DMS is twisted in the trunk in order to visualize the sonograms on the monitor during the neonatal head examination. (Image courtesy of Dr. Evans)

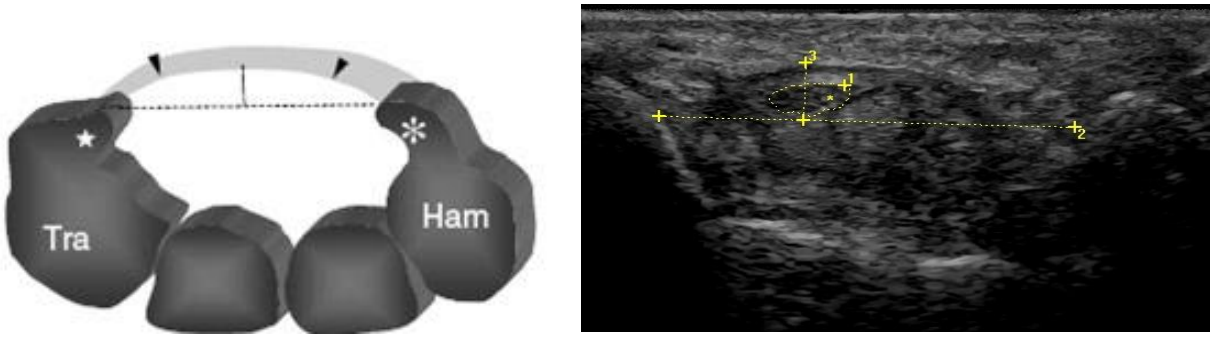


Figure 1.3: Transverse sonogram of the carpal tunnel and the area of the median nerve in the compartment. Note how hypervascularization would impact the area under the retinaculum. Image is provided with kind permission from Springer Publications. [17]

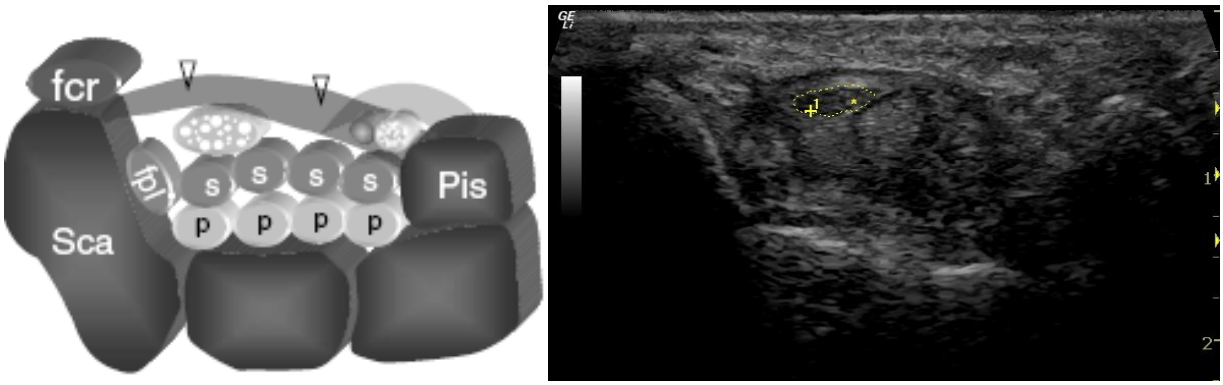


Figure 1.4: Transverse sonogram of the carpal tunnel at the hamate level demonstrating the bulge measurement. Image is provided with kind permission from Springer Publications. [17]

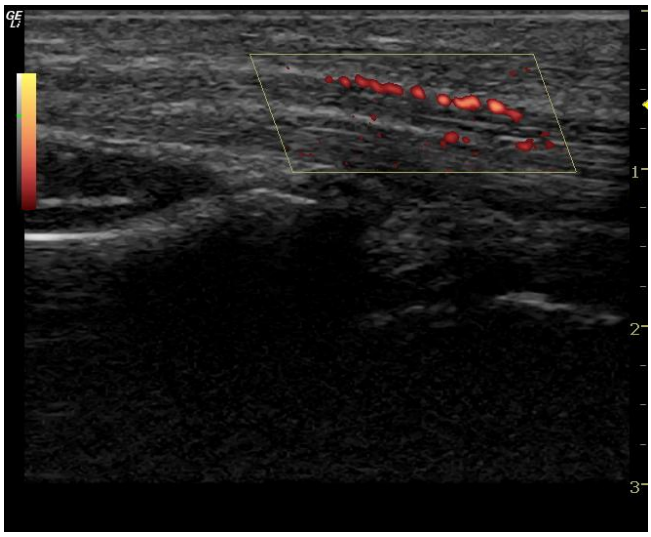


Figure 1.5: Sagital sonogram of the median nerve at the distal radius demonstrating the use of power Doppler to detect arteriole blood flow.

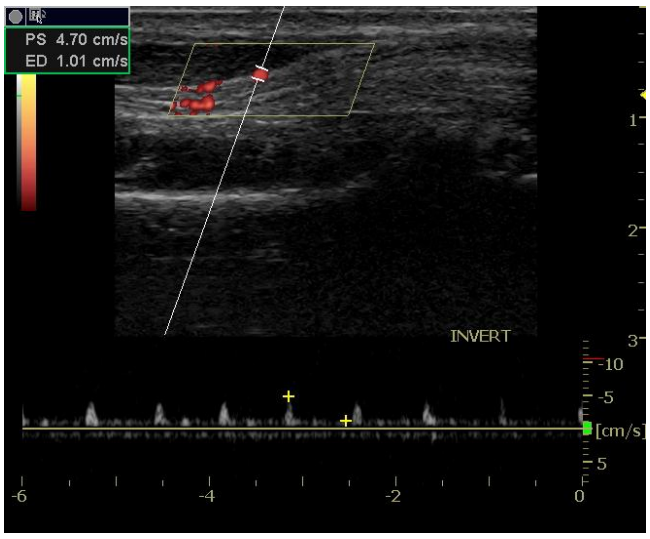


Figure 1.6: Duplex display showing power and spectral gate at the top and spectral wave form below. Peak sytolic measurement = 4.7 cm/s and end diastolic measruement = 1.01 cm/s.

CHAPTER 2

MATERIALS AND METHODS

Methodology

Since gaps in the literature exist, a rigorous and quantitative analysis to detect hypervascularization, represented by arteriole blood flow in the median nerve was needed. This undergraduate research project, which is nested within a larger research project[4], analyzed the blood flow in the nerve sheath by both power Doppler and spectral waveform Doppler. It is important to reiterate that Doppler of perineural blood is what was accomplished.

Internal Review Board (IRB) approval was needed for this project as the participants were human subjects. The proposal of the study was sent to the IRB for approval and included participant criteria, risks and benefits, confidentiality, data collection methods, recruitment and consent. The study was granted Biomedical IRB approval.

A hand carried ultrasound unit provided by GE Healthcare was used to perform sonography examinations on five subjects, each undergoing four scanning sessions, with one subject having an extra fifth ultrasound. Measurements were taken before and post-exercise (neonatal scanning) of both the right and left wrist. Therefore, 84 scans were performed in total.

The five subjects sat facing the examiner with the shoulder slightly flexed, elbow extended, forearm supinated, forearm and wrist rested comfortably on a flat surface, the wrist in neutral and the fingers relaxed in a natural semi-flexed position. A longitudinal grayscale image of the median nerve

was taken at the level of the pisiform or proximal carpal tunnel. (See Figures 2.1- 2.3 for related anatomy diagrams.) Power Doppler, being the most sensitive to flow, was then utilized to document low blood flow in and around the neural sheath. Once this low blood flow was found with power Doppler, the spectral Doppler gate was put over the most consistent flow and a spectral waveform was obtained. Quantitative measurements including peak systole (PS) and end diastole (ED) were then taken from this information.

Population and Sample

The sample population was recruited from The Ohio State University Medical Center's and Nationwide Children's Hospital Radiology departments. The sample of five DMS actively conducted intercranial sonography. Scanning the neonatal brain within the isolette was proposed and results in increased work-related risk to the wrist and forearm of the DMS. These DMS consented voluntarily and were aware they are able to withdraw from the research at any point.

Design

A threshold of three neonatal brain scans was required before pre and post sonography exams were conducted and included in the study. All data was collected over a 10-week period on a weekly basis. This study is considered a feasibility study and has a pre-experimental research design.

Data and Instrumentation

Specifically, a GE Healthcare Logiq *i* (Milwaukee, WI) hand carried ultrasound system was utilized. Both power and spectral Doppler settings were used to obtain the blood flow information. Power Doppler only provided a subjective assessment of arteriole flow within the nerve sheath by amplitude. Spectral Doppler, however, was used to obtain quantitative systolic and diastolic measurements of the blood flow waveform. The images were obtained within the following strict parameters. An optimized musculoskeletal setting was utilized along with a 12 MHz linear array transducer. Spectral Doppler was obtained in duplex mode, where the grayscale and power Doppler

image is static with only a live waveform available. This was used over the triplex, or live power Doppler mode, because it consumes less of the machine's processing power, thus increasing sensitivity for picking up low blood flow. Table 2.1 shows all of the specific sonographic parameters used in this study.

Figure 2.1: Image of a hand demonstrating the scanning plane needed to obtain the sagital image of the median nerve and Doppler values of blood flow. Image is provided with kind permission from Springer Publications. [17]

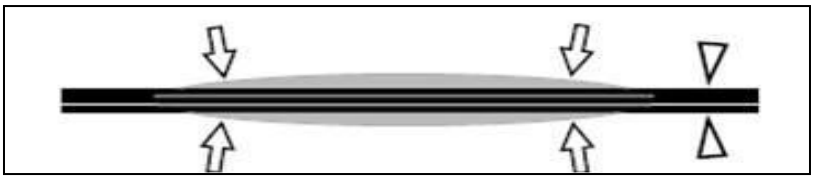


Figure 2.2: Schematic drawing of an acute insult to the median nerve demonstrating swelling of the nerve sheath (arrows) around the nerve and fascicles (pointers). Image is provided with kind permission from Springer Publications. [17]

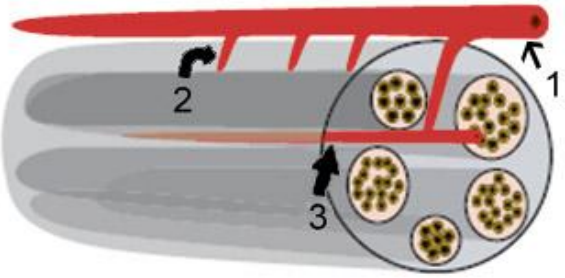


Figure 2.3: (1) Perineural vessels coursing along the nerve (2) Branches which pierce the outer epineurium and (3) Microvasculature among the neural fascicles. Image is provided with kind permission from Springer Publications. [17]

HCU	GE Healthcare Logic *i* (Milwaukee, WI)
Transducer	12 MHz linear
Depth	3 cm
Overall Gain	65 dB
TGC	Vertical and centered
Power Doppler Gain	14-21 dB
Power Doppler PRF	0.4 - 0.6 kHz
Spectral Doppler Gain	26-32 dB
Spectral Doppler PRF	2.6 kHz
Spectral Doppler sample volume	2mm
Processing	Harmonics and Crossbeam® Technology

Table 2.1: Equipment and setting specifications

CHAPTER 3
CONCLUSION

Results

While this is a feasibility study, many of the results are descriptive in nature and simple statistics are reported that relate to the achievability of the Doppler technique. Most of the data collected is reported with means and modes. A power analysis was not possible due to the small *N*. All of the female sonographers conducted the intercranial sonography exams with their right hand and the mean age of the DMS was 43 years (SD 17.6) with a mean sonography work experience of 16.7 years (SD 3.4).[4] The overall results showed that median nerve sheath arteriole blood flow could be detected with Doppler sonography. However, there were discrepancies between the power Doppler and spectral Doppler results. The sensitive power Doppler detected blood flow within the median nerve sheath 100% of the time on both wrists for both pre and post-neonatal head scanning. While this was the preferred result, the information is only qualitative. In contrast, the quantitative spectral Doppler was only obtained in 50% of the total 84 examinations performed. Table 3.1 shows the breakdown of the successful spectral Doppler obtained by each examination by pre/post and right/left.

Even though the data collected by the spectral Doppler was not consistently obtained, the information was dependable. Table 3.2 demonstrates the peak systolic and end diastolic measurement averages from each type of examination broken down again by right/left and pre/post. The averages show a very low flow state, with the overall peak systolic average of 4.36 cm/s and an average end

diastolic average of 0.76 cm/s. These measurements had to be adjusted manually owing to the inherent low flow which was not properly evaluated with the auto-calculation software. The resistive and pulsatility indices were also calculated and averaged in this table. Appendix A describes calculation for a pulsatility index and Appendix B the calculation for a resistive index. The pulsatility index was also obtained manually by following the spectral tracing for a single cardiac cycle. Figure 3.1 shows how the pulsatility tracing for the mean velocity average was traced. The overall average resistive index was 0.83 and the average pulsatility index was 2.97.

Statistical significance was defined as a P value ≥ 0.05 for the t-test. No statistical significances were noted between pre and post exercise of the right scanning hand; peak systolic velocity ($P = 0.96$), end-diastolic velocity ($P = 0.25$), pulsatility index ($P = 0.18$), and resistive index ($P = 0.12$). Significant values were obtained with the statistical software Instat+ v3.36 for Windows operating system. Table 3.3 shows the results including mean, standard error, confidence interval, and p-value for this statistical test.

Initially, the quantitative spectral Doppler information was arranged to be the independent variable to correlate with the use of a Spearman's correlation coefficient to the dependent variable of reported UST pain, represented by the ordinal measure of the Visual Analog Scale for Pain. Since there were no significant findings within the data, however, this correlation was not performed.

Figure 3.2 shows a boxplot for all of the data to visually demonstrate the statistical insignificance found in the results. Also, all of the raw data can be found in Appendix C.

Discussion

Implications of this study may extend far beyond the use of quantifying blood flow related to carpal tunnel; it also relates to calculating inflammation in musculoskeletal sonography. The current gold standard of NCV and dynamic contrast enhanced MRI are both invasive procedures, each with

their drawbacks, like cost and limitations.[10] If hypervascularization can be detected and quantified it could provide a cheaper, portable, non-invasive, non-ionizing examination to detect hypervascular arteriole flow, which could equate to developing CTS. Other future uses could include synovial inflammation, tendonitis, vasculitis, Raynaud's disease, and rheumatoid arthritis.[9]

This independent study was the first of its kind to detect and quantify arteriole blood flow, representative of inflammation, within the median nerve sheath of DMS utilizing both power Doppler and spectral Doppler. The results show that HCU is a feasible imaging method for detection of vascular flow in the nerve sheath. However, power Doppler was more consistent than spectral Doppler and it is pertinent to mention the limitations of this study.

The chief problems encountered with this project were only capturing Doppler for one job duty, neurosonography, and evaluating a small number of subjects over a limited time. The neonatal study is only one of a multitude of studies in a day shift full of many other complex sonographic procedures and portable examinations. Therefore, sonographers may be more likely to demonstrate inflammation within the median nerve at the end of a shift and this study did not portray the complete DMS workload. Additionally, while nested within the work day, there was an inherently limited amount of time to perform the wrist sonograms. While this was part of a larger study, up to eight other sonographic images were obtained on a single wrist, including the bulge and nerve area measurements leaving little to focus on the Doppler measurements. To build on this feasibility study more sonographers should be recruited and an entire day should be considered with pre-Doppler measures being made at the beginning of the shift and post-Doppler measures made again at the end of the shift. Furthermore, the time frame of only 10 weeks was limited and a longitudinal study design would be needed to pick up more than acute inflammation. Therefore, increasing the sample size *N* by following more sonographers over a longer amount of time would give more reliable results.

Another pitfall to this study was the unknown health history of the subjects involved. While all five subjects were asymptomatic for CTS no history was taken on prior injuries or other extraneous wrist stressors that would lead to this nerve entrapment syndrome. It therefore may be easier to stage a controlled study to obtain reliable pre and post data. An example of this would be a longitudinal animal study to control for any outside injury to the median nerve within the carpal tunnel.

The final pitfall to mention is the pre-experimental design of the research therefore making it susceptible to every possible threat, meaning the results cannot be generalized beyond the group of subjects that were tested.

Since only 50% of the sessions yielded quantitative Doppler data it may be too difficult to reliably capture perineural flow. One suggestion would be to isolate a larger artery, which can be observed more readily. In a study of 26 patients with documented CTS and a control group of 35 healthy asymptomatic patients, the lower branches of the hand arteries were evaluated with spectral continuous wave Doppler. A pulsatility index was obtained for both the radialis indices artery and the radial palmar digital artery pre and post sympathetic stimulation (a deep breath followed by a cough.) The study found no significance in the maximal increase in the pulsatility index of the radial palmar digital artery between both groups, however the pulsatility index was significantly lower ($P = 0.037$) in the CTS group for the radialis indices artery. Furthermore, all but two of the radialis indices artery from the CTS group and one radialis indices artery from the control group could be identified.[23]

The above study shows promise in evaluating larger arteries to obtain more consistent quantitative results. A pitfall of the above study is the use of continuous wave versus pulsed wave Doppler. A clear disadvantage of continuous wave Doppler is no image is created and therefore no record of location exists; only a spectral tracing is acquired. With pulsed wave Doppler, as used in

this pilot study, a clear image of the radialis indices artery may be obtained and recorded. The combination of getting a clear image by using pulsed wave Spectral Doppler and a larger artery would allow for a consistent Doppler shift of 60° to be obtained for each tracing, adding to reproducibility.[22]

The pulsatility index of this study showed a slight decrease of 0.83 from the average right-pre to right-post examinations, 3.24 and 2.41 respectively. While this decrease is not significant, likely due to the low *N*, it follows the same pattern observed in the study which used sympathetic stimulation. While similar outcomes exist between these asymptomatic patients and the known CTS patients, a different physiology is being measured and this is because the pulsatility index is a measure of vasoconstriction. In normal sympathetic stimulation the pulsatility index would increase due to peripheral arteriolar vasoconstriction. A decrease in pulsatility would indicate, as the study showed, the vasomotor fibers in those patients with CTS are abnormal.[23] In the present study, the pulsatility index predictably decreased due to vasodilatation of the arterioles which is normal after vigorous exercise because the capillary beds open and therefore flow resistance decreases.[22] The resistive index in the pilot study, which also measures vasoconstriction, follows the pulsatility index and resistance decreased in the DMS wrist by 0.87 pre-right to 0.78 post-right, which would suggest the arterioles were vasodilated after the neonatal head scanning.

While this study looked at the arteriole blood flow proximal to the carpal tunnel the little vasodilatation observed here is likely associated with a normal physiologic response versus any developing disease. However, if a proximal location were to be utilized in the future to detect for inflammation, the radial artery would be a larger artery to capture. Hypothetically, reactive hyperemia could emanate and be physiologically fed from the radial artery and a guideline could be suggested to differentiate between normal vasodilatation and pathological vasodilatation.

Yet, if a distal artery to the carpal tunnel, such as the radialis indices artery, were observed for a future study blood flow would be diminished and a likely decrease in both systolic flow and end diastolic flow would be seen as the hand becomes ischemic. A normal response to exercise in the distal arteries would be the same decrease to resistance as the arterioles are vasodilated to allow for more blood flow. Whether differentiating between hyperemia proximal to the carpal tunnel or ischemia distal to the carpal tunnel, blood flow is expected to be altered in patients with known CTS. It is therefore important for future studies to include known patients with CTS and compare them with asymptomatic patients for a better controlled design.

An additional suggestion for any future study would be to utilize a high-end ultrasound machine in lieu of a HCU that would provide sophisticated Doppler tracings of this discrete area of the wrist. This may include utilizing a higher frequency transducer with a lower Doppler pulse-repetition frequency or PRF. This pilot study was performed in duplex mode to increase the Doppler sensitivity, but it would be preferred to use a triplex mode if possible. In triplex the power Doppler is not frozen, allowing the operator to know where to correctly place the spectral gate in case any slight movements off set the true location of the vessel.[22] A more sophisticated ultrasound unit may provide these favorable results when looking at perineural blood flow.

In conclusion, further investigation of Doppler waveforms in the median nerve sheath is warranted to determine diagnostic and/or research uses.

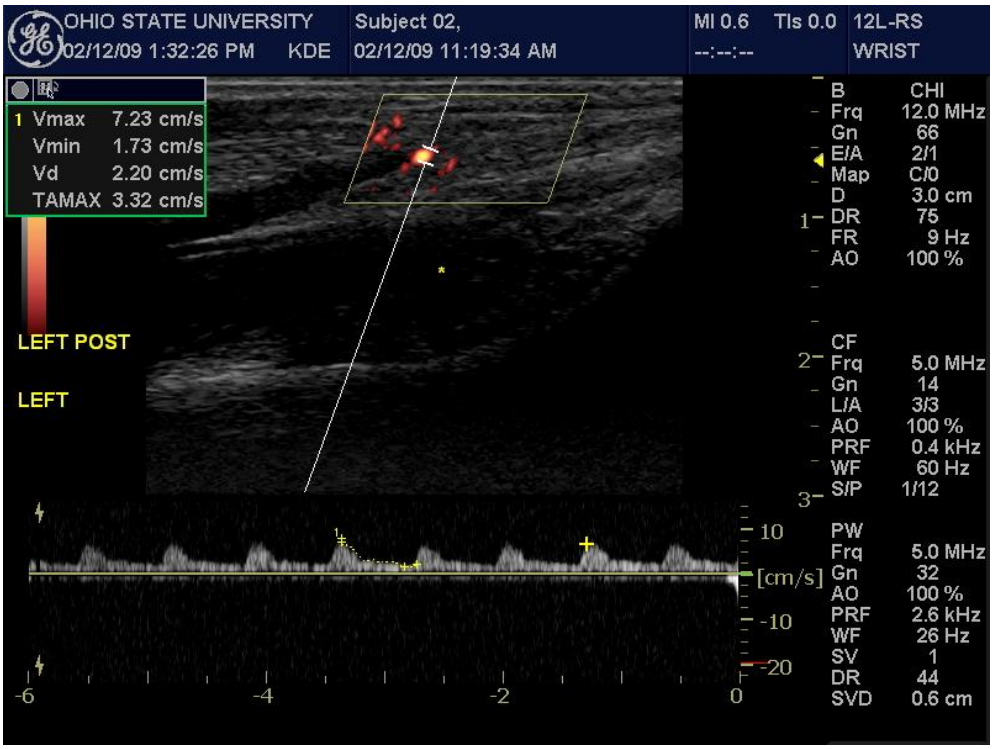


Figure 3.1: A manual spectral tracing during a cardiac cycle to obtain the mean average velocity in order to calculate the pulsatility index.

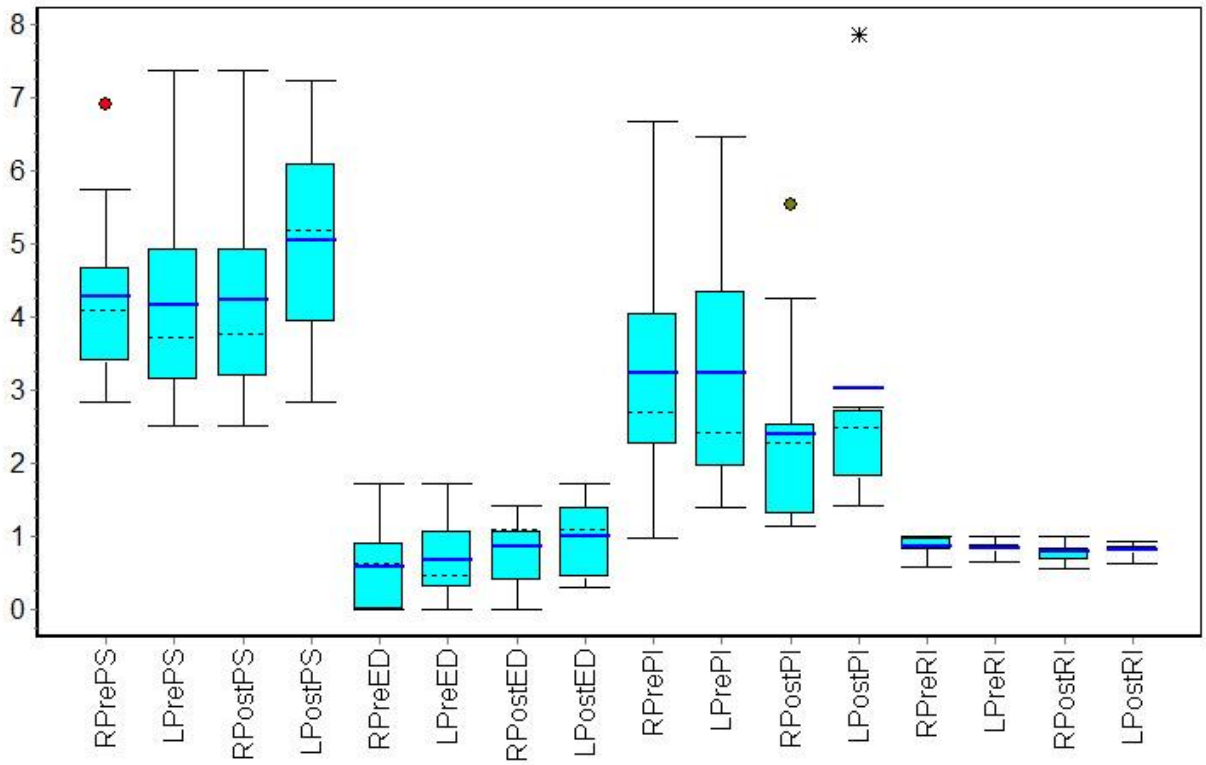


Figure 3.2: Boxplot Diagram of each type of exam including the peak systolic, end diastolic, pulsatility index and resistive index values.

Scan	# obtained	# performed	percent
Pre-Right	11	21	52%
Pre-Left	12	21	57%
Post-Right	12	21	57%
Post-Left	7	21	33%
Total	**42**	**84**	**50%**

Table 3.1: Total number of examinations performed and number of successful spectral Doppler obtained.

Scan	PS Avg.	ED Avg.	PI Avg.	RI Avg.
Pre-Right	4.28	0.59	3.24	0.87
Pre-Left	4.16	0.68	3.24	0.84
Post-Right	4.25	0.85	2.41	0.78
Post-Left	5.05	1.01	3.02	0.81
Total Averages	**4.36**	**0.76**	**2.97**	**0.83**

Table 3.2: Mean averages of the measured peak systolic (PS) and end-diastolic (ED) velocities, as well as the calculated pulsatility index (PI) and resistive index (RI) mean averages.

	Right Pre Scan (n=11)			Right Post Scan (n=12)			
Index	Mean	SE	95% CI	Mean	SE	95% CI	P
PS	4.28	0.37	3.46 - 5.09	4.25	0.44	3.28-5.21	0.96
ED	0.59	0.18	0.18 - 0.99	0.85	0.13	0.55 - 1.15	0.25
PI	3.24	0.47	2.20 - 4.28	2.41	0.38	1.57 - 3.24	0.18
RI	0.87	0.04	0.79 - 0.96	0.78	0.04	0.69 - 0.87	0.12

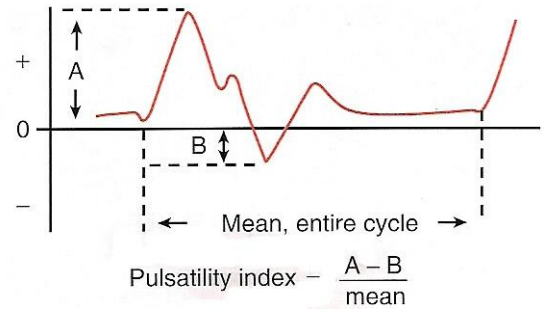
Table 3.3: Statistical t-test results comparing the right wrist measurements pre and post exercise. CI indicates confidence interval.

APPENDIX A

Calculating a Pulsatility Index

$$\text{Pulsatility Index (PI)} = \frac{V_{max} - V_{min}}{V_{max\ mean}}$$

Where V_{max} is the peak systolic (PS) velocity, V_{min} is the end diastolic (ED) velocity, and $V_{max\ mean}$ is the maximum velocity averaged over one cardiac cycle. Below is a schematic drawing showing the spectral Doppler tracing and how the pulsatility index is derived.[24]



24

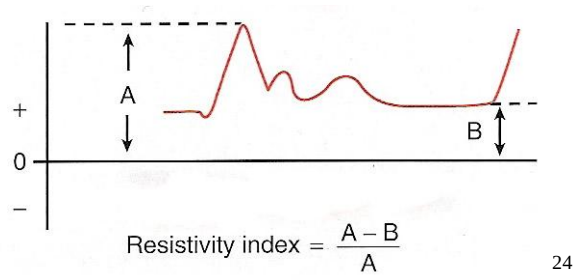
PI: A = peak systole above baseline, B = end diastole below baseline, Mean of an entire cycle below
Pulsatility index = A-B/ Mean[24]

APPENDIX B

Calculating a Resistive Index

$$\text{Resistive index (RI)} = \frac{V_{max} - V_{min}}{V_{max}}$$

Again, V_{max} is the peak systolic (PS) velocity and V_{min} is the end diastolic (ED) velocity. Below is a schematic drawing showing the spectral Doppler tracing and how the resistive index is derived.[24]



24

RI: A = peak systole above baseline, B = end diastole below baseline
Resistive index = A-B/ A[24]

APPENDIX C

Raw Data Results

Pre-Spectral Doppler Data Table

Pre-Spectral Doppler Scan of the Right Wrist

Subject	Scan	Pre PS	Pre ED	Pre PI	Pre RI
1	1	4.64	0.71	2.31	0.85
	2	2.99	0	2.65	1.00
	3	x	x	x	x
	4	x	x	x	x
2	1	4.09	1.73	0.98	0.58
	2	4.09	0	3.38	1.00
	3	4.72	0	4.10	1.00
	4	6.92	1.42	1.99	0.79
3	1	x	x	x	
	2	x	x	x	x
	3	2.83	0	4.04	1.00
	4	x	x	x	x
4	1	x	x	x	x
	2	4.09	0.31	4.55	0.92
	3	5.74	1.02	2.71	0.82
	4	3.3	0.63	6.68	0.81
	5	3.62	0.63	2.25	0.83
5	1	x	x	x	x
	2	x	x	x	x
	3	x	x	x	x
	4	x	x	x	x

Pre-Spectral Doppler Scan of the Left Wrist

Subject	Scan	Pre PS	Pre ED	Pre PI	Pre RI
1	1	x	x	x	x
	2	x	x	x	x
	3	4.4	0.79	2.16	0.82
	4	7.39	1.73	2.07	0.77
2	1	x	x	x	x
	2	3.3	0.63	1.83	0.81
	3	4.4	1.42	1.39	0.68
	4	3.3	0.31	4.04	0.91
3	1	x	x	x	x
	2	x	x	x	x
	3	5.82	0.79	2.34	0.86
	4	5.5	0	3.74	1.00
4	1	x	x	x	x
	2	x	x	x	x
	3	3.38	0.08	6.47	0.98
	4	4.09	1.42	1.47	0.65
	5	2.83	0.31	2.50	0.89
5	1	x	x	x	x
	2	x	x	x	x
	3	2.52	0.31	4.70	0.88
	4	2.99	0.31	6.23	0.90

Post-Spectral Doppler Data Table

Post-Spectral Doppler Scan of the Right Wrist

Subject	Scan	Post PS	Post ED	Post PI	Post RI
1	1	2.59	0.39	2.42	0.85
	2	x	x	x	
	3	x	x	x	x
	4	x	x	x	x
2	1	x	x	x	x
	2	3.62	1.42	1.24	0.61
	3	3.93	0	4.27	1.00
	4	5.19	0.79	2.23	0.85
3	1	x	x	x	x
	2	x	x	x	x
	3	x	x	x	x
	4	x	x	x	x
4	1	3.62	1.1	1.39	0.70
	2	3.38	0.39	2.35	0.88
	3	7.39	1.1	2.61	0.85
	4	6.61	1.1	2.52	0.83
	5	4.4	0.31	5.53	0.93
5	1	2.99	1.1	1.13	0.63
	2	4.72	1.42	2.01	0.70
	3	x	x	x	x
	4	2.52	1.1	1.20	0.56

Post-Spectral Doppler Scan of the Left Wrist

Subject	Scan	Post PS	Post ED	Post PI	Post RI
1	1	x	x	x	x
	2	x	x	x	x
	3	x	x	x	x
	4	5.19	0.79	2.68	0.85
2	1	7.23	1.73	1.66	0.76
	2	3.93	1.42	1.42	0.64
	3	x	x	x	x
	4	x	x	x	x
3	1	x	x	x	x
	2	x	x	x	x
	3	x	x	x	x
	4	6.13	1.1	2.78	0.82
4	1	x	x	x	x
	2	x	x	x	x
	3	x	x	x	x
	4	3.93	0.31	7.87	0.92
	5	2.83	0.31	2.50	0.89
5	1	x	x	x	x
	2	x	x	x	x
	3	6.13	1.42	2.23	0.77
	4	x	x	x	x

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